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Titan's magnetic field signature during the Cassini T34 flyby: Comparison between hybrid simulations and MAG data

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[1] During the T34 flyby on 19 July 2007, the Cassini spacecraft passed through the magnetic pile-up region at Titan's ramside. The magnetic environment of Titan during this flyby is studied using a three-dimensional hybrid simulation model. This approach treats the electrons of the plasma as a massless, charge-neutralizing fluid, whereas the effects of finite ion gyroradii are taken into account by modeling the ions as individual particles. The simulation results are compared to data collected by the Cassini Magnetometer Instrument. The key features of the measured magnetic field signature have shown to be fully reproducible in the framework of the simulation model. Several signatures in the observed magnetic field can be ascribed to the passage of the Cassini spacecraft through the magnetic barrier upstream of Titan. **Citation:** Simon, S., U. Motschmann, G. Kleindienst, K.-H. Glassmeier, C. Bertucci, and M. K. Dougherty (2008), Titan's magnetic field signature during the Cassini T34 flyby: Comparison between hybrid simulations and MAG data, *Geophys. Res. Lett.*, *35*, L04107, doi:10.1029/2007GL033056.

1. Introduction

[2] The exploration of Saturn's largest moon, Titan, and its highly variable plasma environment is a major purpose of the ongoing Cassini mission. By the time of this writing, more than 35 flybys of Titan have already been accomplished, each of them providing a diversity of new information on the interaction between the moon's dense, nitrogen-rich atmosphere and the corotating Saturnian magnetospheric plasma flow. The analysis of the data collected during these flybys is supported by global numerical simulations, such as the MHD approaches recently presented by *Ma et al.* [2006], *Neubauer et al.* [2006], and *Backes* [2005], or the hybrid approaches of *Kallio et al.* [2004], *Simon et al.* [2006b, 2007a, 2007b], and *Simon* [2007].

[3] In the present study, we shall focus on the magnetic field observations during the T34 flyby of Titan on 19 July 2007. During this flyby, the Cassini spacecraft passed through the magnetic pile-up region at Titan's ramside, with the spacecraft trajectory being almost completely located in Titan's orbital plane. The purpose of this work is to compare the observations of the Cassini magnetometer (MAG) instrument [*Dougherty et al.*, 2004] to the results of a three-dimensional hybrid simulation of the flyby scenario. The hybrid approach treats the electrons of the plasma as a charge-neutralizing fluid with vanishing inertia, while the ions are modeled as macroparticles. Recently, our hybrid model has been successfully applied to explain some features of the magnetic field observations during Cassini's ninth flyby of Titan in December 2005 [*Simon et al.*, 2007c].

2. Flyby and Simulation Parameters

[4] Cassini's T34 flyby of Titan took place on 19 July 2007. The spacecraft achieved its closest approach altitude of 1332 km at 01:11 UT. During the flyby, Titan was located at 18:50 Saturnian local time on its orbit around Saturn; that is, the dayside and the ramside hemisphere of Titan were nearly identical [see also *Simon et al.*, 2006b]. Titan was located inside Saturn's magnetosphere. The flyby trajectory of T34 is illustrated in Figure 1. The coordinate system that is used throughout this paper is the Titan Interaction System [*Backes et al.*, 2005; *Backes*, 2005], whose X axis is aligned with the direction of ideal corotation. The Y axis is also located in Titan's orbital plane and points towards Saturn. The Z axis completes the right-handed coordinate system and is therefore perpendicular to Titan's orbital plane, pointing northward. During the flyby, the trajectory of Cassini was almost completely located inside Titan's orbital plane, i.e., $Z_{\mathrm{Cassini}} \approx 0$. As can be seen from Figure 1, the spacecraft approached Titan from the anti-Saturn-facing ($Y < 0$) side, while the outbound part of the trajectory is located in the ($Y > 0$) hemisphere of the moon.

[5] The purpose of this study is to reproduce the magnetic field signature detected by the MAG instrument within the framework of a hybrid plasma simulation. The simulation model used for this study has been discussed in detail in our companion papers mentioned above. In recent years, the model has not only been successfully applied to the plasma interaction of Titan, but the plasma environments of Mars [*Bößwetter et al.*, 2004], of magnetized asteroids [*Simon et al.*, 2006a] and weak comets [*Bagdonat and Motschmann*, 2002; *Motschmann and Kührt*, 2006] have also been studied. Recently, this simulation approach has been extended to the case of non-stationary upstream conditions, allowing to study the development of Titan's pick-up tail in a varying electromagnetic environment [*Simon et al.*, 2008].

[6] Therefore, only a brief overview of the major simulation parameters shall be given. In the model, Titan is assumed to be exposed to a subfast magnetospheric plasma flow, consisting of oxygen (O^+) and hydrogen (H^+) ions. This is consistent with the original findings of Voyager 1. The upstream densities are $n(O^+) = 0.2 \cdot 10^6\ \mathrm{m}^{-3}$ and $n(H^+) =$

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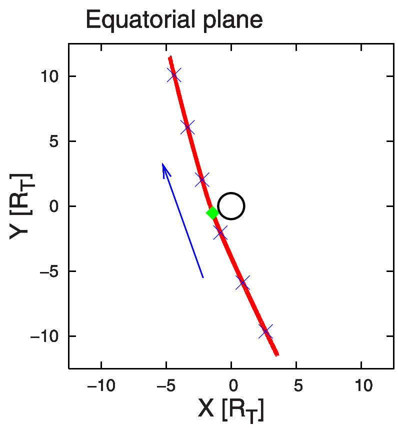

Figure 1. Cassini's trajectory during the T34 flyby of Titan. The spacecraft achieved its closest approach altitude of 1332 km on 19 July 2007 at 01:11 UT. The position of closest approach is denoted by a green diamond. The blue crosses along the trajectory denote Cassini's position in intervals of 30 minutes, starting at 00:00 UT. The spacecraft trajectory is completely located in the (X, Y) plane of the Titan Interaction System. The X axis is aligned with the direction of ideal corotation; the Y axis points from Titan to Saturn. The angle between the direction of ideal corotation and the impinging solar radiation is about 12.5°.

$n(O^+)/2$, respectively. The upstream flow speed has been set to $\underline{u}_0 = 120$ km/s $\underline{e}_X$, where $\underline{e}_X$ is aligned with the X axis of the Titan Interaction System. The temperatures of both ion species have been chosen in such way that their thermal velocities have the same value of v_{th} = 180 km/s. The temperature of the charge-neutralizing magnetospheric electrons has been set to $kT = 200$ eV. The ambient magnetic field vector has been set to $\underline{B}_0 = (-0.5, 2.5, -2.0)$ nT, which can be considered a reasonably good approximation to the homogeneous segments in the signatures detected by the Cassini magnetometer (blue lines in Figure 2). The magnetic field magnitude is therefore given by $|\underline{B}_0| = 3.24$ nT. In contrast to the classical Voyager 1 geometry of the Titan interaction, the magnetic field vector is not perpendicular to the (X, Y) plane. Therefore, the satellite's magnetic lobes are not confined to the (X, Z) plane, as it was the case in our preceding simulation studies. Titan faces a subsonic (sonic Mach number: M_S = 0.82) and submagnetosonic (magnetosonic Mach number: M_{MS} = 0.79), yet super-Alfvenic (Alfvenic Mach number: M_A = 3.08) magnetospheric plasma flow.

[7] Titan's ionosphere is assumed to consist of three ion species of representative masses: molecular nitrogen, methane and molecular hydrogen. The satellite's dayside ionosphere is assumed to be generated exclusively by solar UV radiation and is therefore represented by a Chapman layer; that is, a dependency of the production rate on the altitude above the surface as well as on the solar zenith angle is included. Particle impact processes at the nightside have been approximated in a phenomenological way by including a production profile that depends only on the altitude above the surface. The obstacle boundary, being defined by an absorptive sphere, is located at an altitude of 300 km above the surface of Titan. The model does not include a self-consistent treatment of particle impact processes. Besides, the hybrid approach is not (yet) capable of covering complex chemical reactions, like some of the MHD codes. The detailed parameters of our Titan ionosphere model are discussed in our companion papers [*Simon et al.*, 2006b, 2007b]. The simulations are carried out on an equidistant

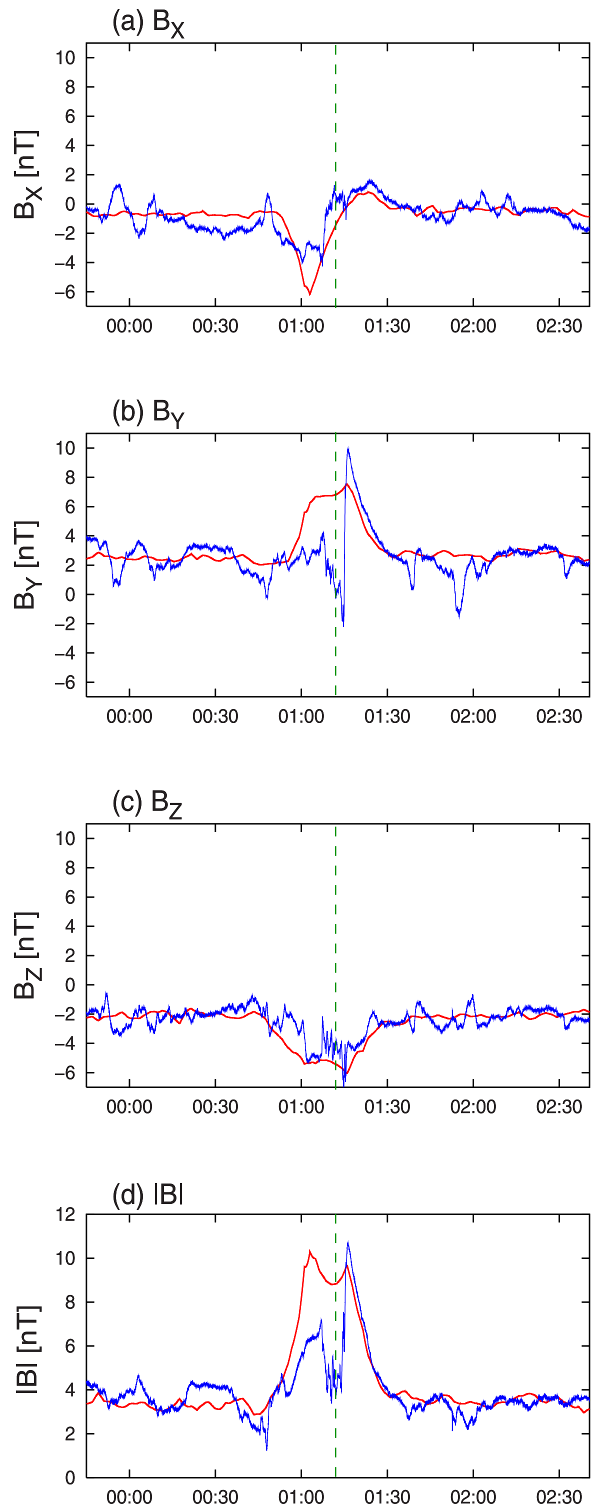

Figure 2. Titan's magnetic field signature during the T34 flyby: Hybrid simulation results (red lines) versus Cassini Magnetometer data (blue lines). The closest approach at 01:11 UT is denoted by the dashed green lines. The measured signature consists of about 10000 data points.

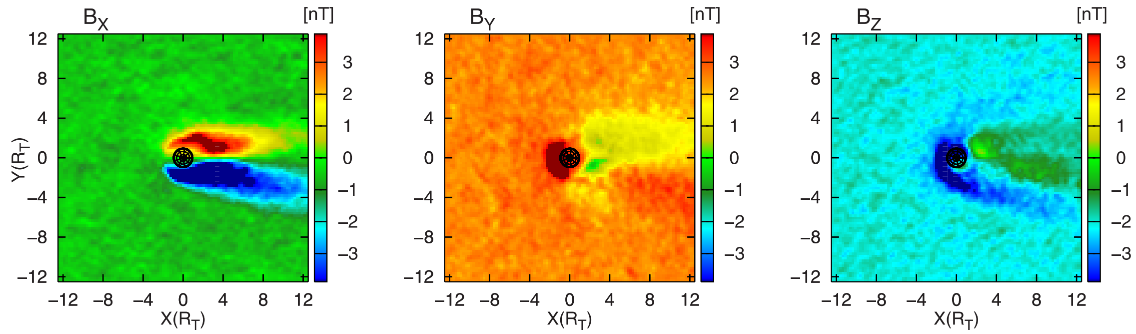

Figure 3. Magnetic field components in the (X, Y) plane of the Titan Interaction System. The corresponding flyby trajectory is shown in Figure 1. The radius of Titan is R_T = 2575 km.

Cartesian grid with an extension of (±15 R_T) × (±15 R_T) × (±15 R_T) (radius of Titan: R_T = 2575 km) and 100 cells in each spatial direction. At the beginning of the simulation, 40 magnetospheric macroparticles are placed in each cell. In addition to this, about 3000 new ionospheric macroparticles are injected into the simulation box during each time step. In the quasi-stationary state, the simulation scenario contains a total number of about 20 million macroparticles.

3. Simulation Results and Discussion

[8] The simulation results are shown in Figures 2 and 3. Figure 2 illustrates the simulated (red lines) and the measured (blue lines) magnetic field signature along Cassini's trajectory. A two-dimensional illustration of the global magnetic field topology in Titan's orbital plane is displayed in Figure 3. Around closest approach at 01:11 UT, the Cassini magnetometer detected a broad dip in the B_X component, denoting a decrease to a minimum value of about $B_X = -4$ nT. This structure is followed by a slightly pronounced overshoot at 01:45 UT, where the B_X component reversed its direction (cf. plot 2 (a)). Both signatures are well reproduced by the simulation model. As illustrated by the red line, the simulated B_X component exhibits a spiky minimum around 01:00 UT, its position coinciding with the structure detected by the Cassini magnetometer. The relative magnitude of the simulated dip is about 2 nT larger than the value detected by Cassini. In the subsequent peak, the simulated B_X component reverses its direction. The magnitude of this distortion is clearly exceeded by that of the dip. This behaviour is in full agreement with the data collected by the MAG instrument.

[9] The formation of the signatures in the B_X component can be understood by means of the two-dimensional illustration in Figure 3. As illustrated by the contour plot, the interaction gives rise to a lobe structure in the B_X component. The lobe in the anti-Saturn-facing hemisphere denotes a decrease of the B_X component, whereas in the Saturn-facing lobe, B_X is increased with respect to the background value. The B_X component is not increased near Titan's ramside. The contour plots show that the B_Y component is the only one that features a strong increase near Titan's ramside. In the same region, the B_X component nearly decreases to its background value of $B_{X,0} = -0.5$ nT. A comparison between Figures 1 and 3 illustrates that when approaching Titan, the Cassini spacecraft first came into contact with the forward region of the anti-Saturn-facing magnetic lobe; that is, the one which is located in the ($Y < 0$) hemisphere. This event is marked by the simulated as well as the measured dip around 01:00 UT. However, after 01:11 UT, the distance between Titan and the Cassini spacecraft continuously increased. Therefore, when Cassini subsequently passed through the forward edge of the Saturn-facing lobe, the distance between the spacecraft and the distorted magnetic environment of Titan was already larger than during the inbound passage through the anti-Saturn-facing lobe. For this reason, the imprint that the Saturn-facing increase of B_X left in the B_X component along the trajectory is a little weaker than the decrease during the passage through the anti-Saturn-facing lobe. In any case, the simulation model illustrates that during the flyby, the spacecraft came into contact with the forward regions of both magnetic lobes. One problem with the B_X component was the definition of an appropriate background value. In the B_X component, it is difficult to find a constant value which represents the inbound as well as the outbound magnetic field in an appropriate way. This might explain the minor difference between the magnitudes of simulated and measured dip.

[10] As already stated above, the simulated B_Y component features a strong enhancement near Titan's ramside. However, in contrast to the B_X component, the simulated B_Y distortions at the wakeside of Titan exhibit a rather diffuse structure (cf. Figure 3). As can be seen from Figure 2b, the passage through the region of increased B_Y near Titan's ramside manifests in the simulated as well as in the measured magnetic field signature. However, the simulation model suggests the pile-up to be broad and plateau-like. The width of the B_Y peak is clearly overestimated by the simulation model, while the simulated B_Y maximum value achieved at Titan's ramside is in reasonable agreement with the measured signature (7.5 nT from the simulation versus 10 nT from measurements). It is also possible that the measured magnetic distortions between 00:45 UT and CA are so small that they cannot be separated from the background field. Although the sharp increase of B_Y near the inbound flank of the measured pile-up is not reproduced by the simulation, model calculations and measurements of B_Y fit quite well in the outbound region of the flyby (cf. Figure 2b). Especially, the steep outbound flank of the B_Y pile-up is well reproduced. It should be noted that for the B_Y component, quantitative agreement between simulated and measured field in the inbound region could not be improved by assuming the magnetospheric upstream flow to deviate

from the direction of ideal corotation. Such an assumption had proven successful for reproducing the magnetic field signatures measured during earlier Titan flybys [*Ma et al.*, 2006; *Simon et al.*, 2007c]. On the one hand, this discrepancy might emerge from the used ionosphere model. In the immediate vicinity of Titan, complex chemical processes might become important, which are not covered by our simulation approach. The minor amount of numerical diffusion which is present in any simulation approach might also take slight influence on the outcome of the simulation in this region. Besides, the grid resolution is not high enough to resolve the ionopause region in detail. Another critical point may be the fact that the simulation model assumes the upstream conditions to be perfectly homogeneous in space and time. As already stated by *Neubauer et al.* [2006], during the first series of Titan flybys, this assumption was not always perfectly fulfilled.

[11] As displayed in Figure 2c, good agreement between simulated and measured magnetic field could be achieved for the B_Z component. The measured B_Z signature features a broad decrease between 01:00 UT and 01:45 UT. Both the location and the relative magnitude of the B_Z reduction are well reproduced by the simulation model. As can be seen from the B_Z contour plot in Figure 3, the simulated B_Z component is reduced in the anti-Saturn-facing hemisphere as well as near Titan's ramside. The passage of the spacecraft through this region of reduced B_Z is responsible for the break-in of the B_Z component.

[12] The simulation results for the magnetic field magnitude can be seen in Figure 2d. The maximum field value of the pile-up is well reproduced by the simulation model. Due to the width of the overshoot in the B_Y component being overestimated by the model, the simulated increase of $|\underline{B}|$ is also broader than the measured field enhancement. However, especially the steep outbound part of the $|\underline{B}|$ enhancement has shown to be fully reproducible by the simulation model. Despite the quantitative differences, the overall structure of the distortion in $|\underline{B}|$ is also well reproduced: Both the model and Cassini data show the formation of a minimum in $|\underline{B}|$, which is accompanied by a maximum at each side. The relative magnitude of the break-in between the two peaks is underestimated by the simulation model. The two spikes in $|\underline{B}|$ may indicate Cassini's crossings through Titan's ionopause.

4. Summary

[13] During the Cassini T34 flyby of Titan, the spacecraft conducted magnetic field measurements in the magnetic pile-up region at Titan's ramside. In this paper, we presented an attempt to reproduce the key features of the observed magnetic field signature by means of a three-dimensional, semi-kinetic plasma model. The simulation results have shown to be in reasonably good agreement with the observations of the Cassini Magnetometer Instrument. A measured break-in of the B_X component, followed by a slightly pronounced overshoot, could be ascribed to Cassini's passage through the forward edges of Titan's magnetic lobes. Although complete quantitative agreement between simulation and measurements could not be achieved, the simulated enhancement of the B_Y component near Titan's ramside is in complete correspondence to Cassini observations. Both the relative magnitude and the location of the measured dip in the B_Z component have shown to be fully reproducible by the simulation model. The results presented in this paper illustrate that global plasma simulations can provide efficient and valuable support for the interpretation of Cassini measurements in the vicinity of Titan.

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